

Aspen winter conference 2023

Manifesting hidden dynamics of a sub-component dark matter

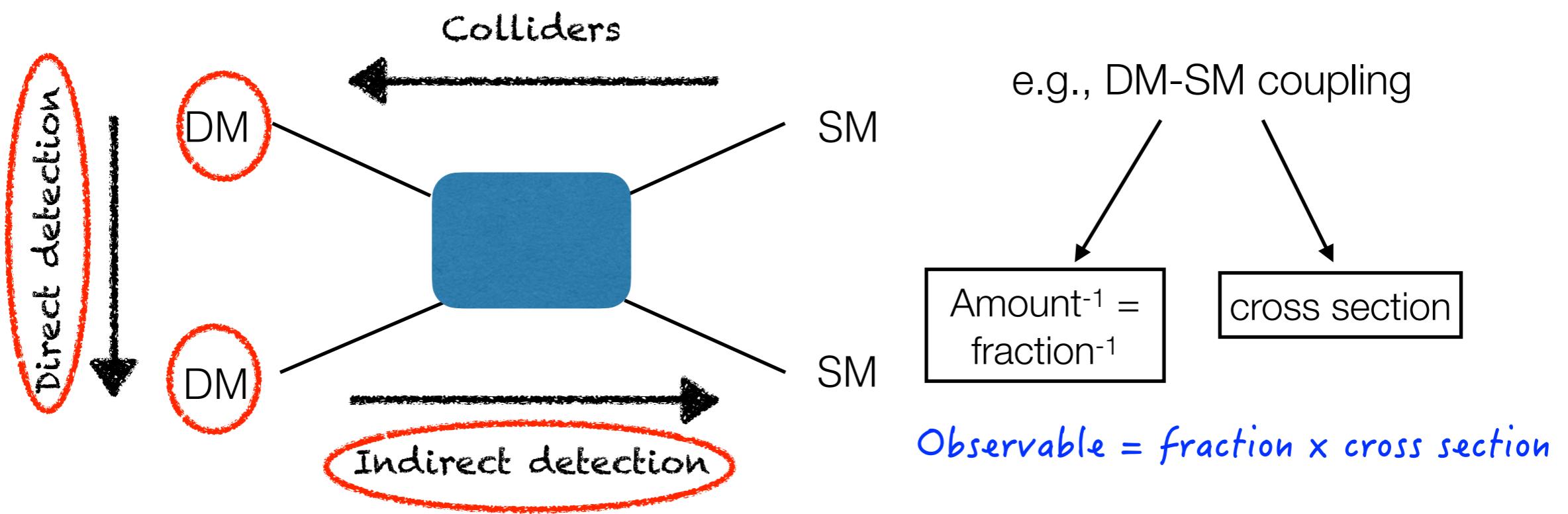
Seodong Shin



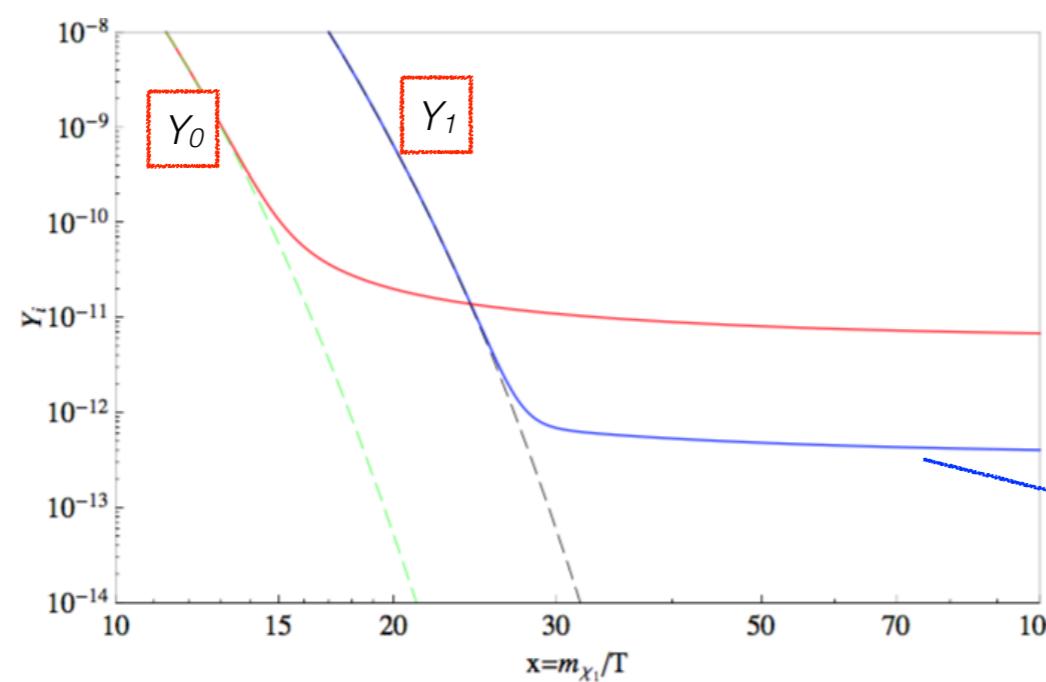
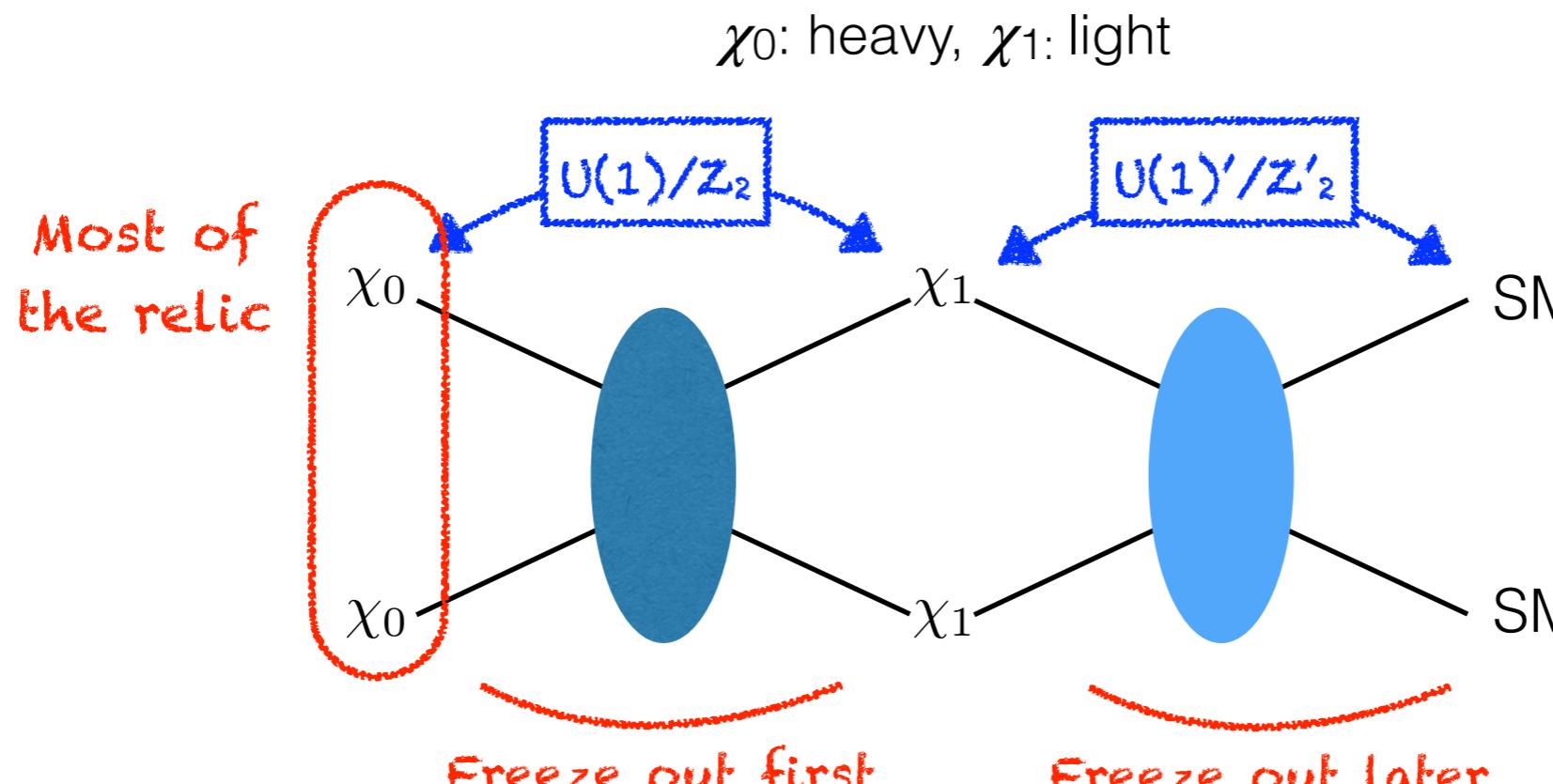
Ayuki Kamada, Hee Jung Kim, Jong-Chul Park, **ss**, JCAP 10, 052 (2022), arXiv: 2111.06808

Sub-dominant component is hidden?

- Conventionally, sub-dominant DM components are thought to be hidden in direct/indirect detection experiments: observables \propto fraction
- The dominant relics might be safe from the experiments so far if it communicates with the SM sector through the sub-dominant relic?
- Question is how the amount of the sub-dominant relic is determined.



Reference: Multi-component BDM



Agashe, Cui, Necib, Thaler, JCAP 2014

Kim, Park , **SS**, PRL 2017

Giudice, Kim, Park , **SS**, PLB 2018

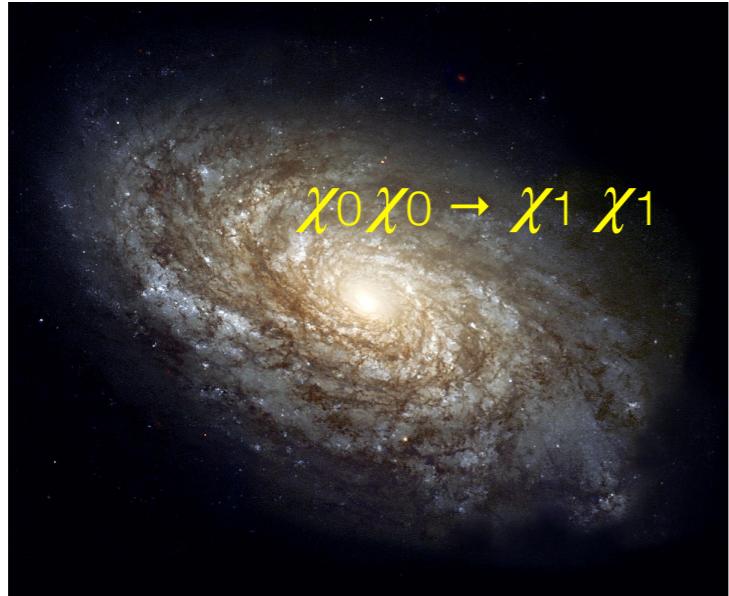
Belanger, Park, JCAP 2012

Assisted freeze-out mechanism

non-relativistic relic χ_1 (negligible)

$$Y_0 \gg Y_1$$

Reference: Multi-component BDM



- χ_0 : accumulated
(GC, Sun, dSphs)
- $\chi_0 \chi_0 \rightarrow \chi_1 \chi_1$ (current universe) **relativistic**
※ relic χ_1 is non-relativistic



Observe χ_1 scattering off target with $E_1 > E_{\text{th}}$
(indirect detection of χ_0)

$$\text{Flux of } \chi_1 \simeq 1.6 \times 10^{-8} \text{ cm}^{-2} \text{s}^{-1} \times \left(\frac{\langle \sigma v \rangle_{0 \rightarrow 1}}{5 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}} \right) \times \left(\frac{100 \text{ GeV}}{m_0} \right)^2$$

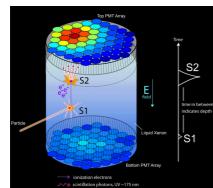
Assume: NFW



Fixed ~ 1 if **s-wave** annihilation dominates (throughout this work for simplicity)



10,000 times smaller than the flux of atmospheric ν if $m_0 \sim 100 \text{ GeV}$



comparable

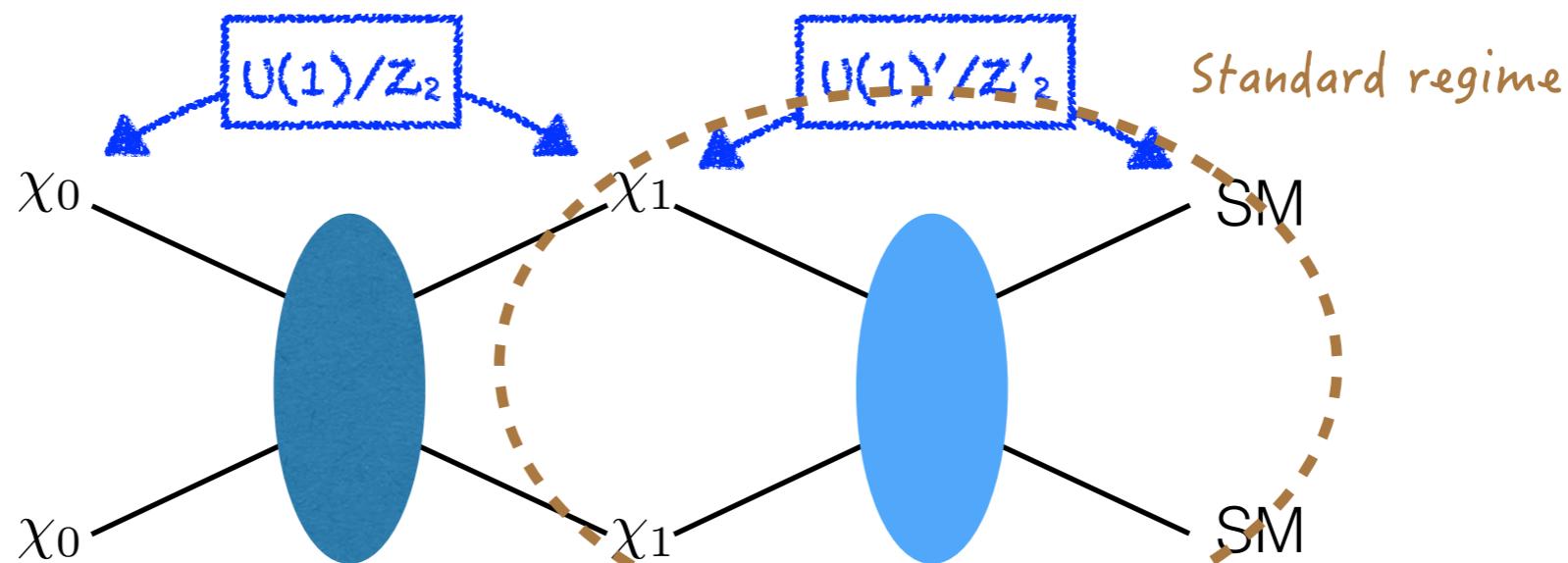
if $m_0 \lesssim 1 \text{ GeV}$

Giudice, Kim, Park , **SS**, PLB 2018

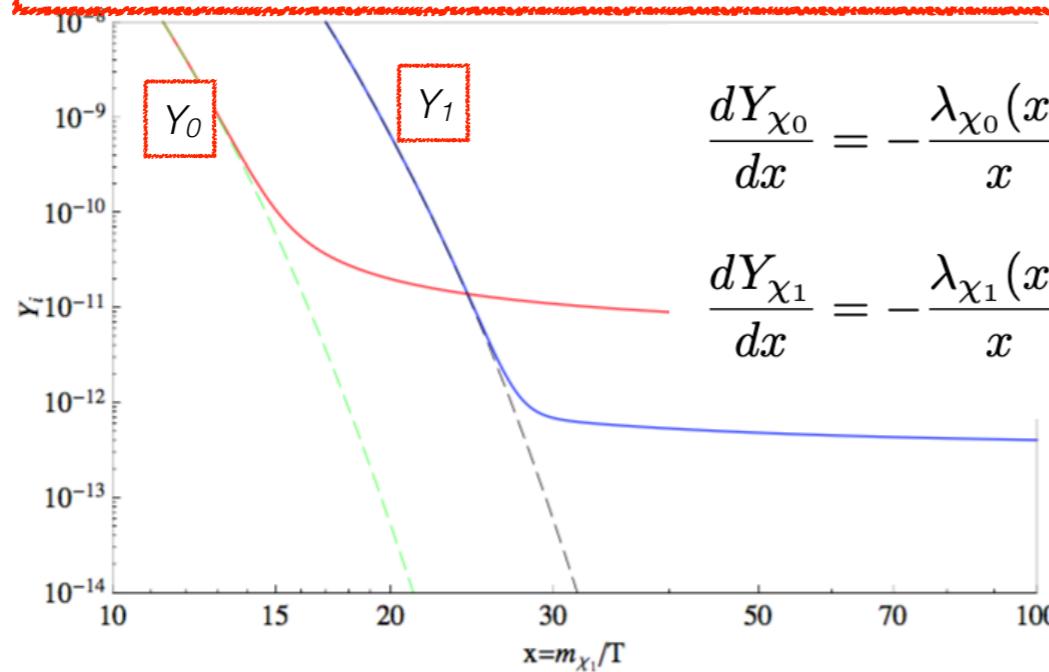
Agashe et al.,
JCAP 2014
Kim, Park , **SS**,
PRL 2017

Structure of $\chi_1\chi_1 \rightarrow \text{SM}$

χ_0 : heavy (dominant), χ_1 : light (subdominant)



Assumption: $\chi_0\chi_0 \rightarrow \chi_1\chi_1$ is *s*-wave & the mediator χ_1 - SM is heavier than χ_1 .



$$\frac{dY_{\chi_0}}{dx} = -\frac{\lambda_{\chi_0}(x)}{x} \left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\text{eq}}(x)}{Y_{\chi_1}^{\text{eq}}(x)} \right)^2 Y_{\chi_1}^2 \right],$$

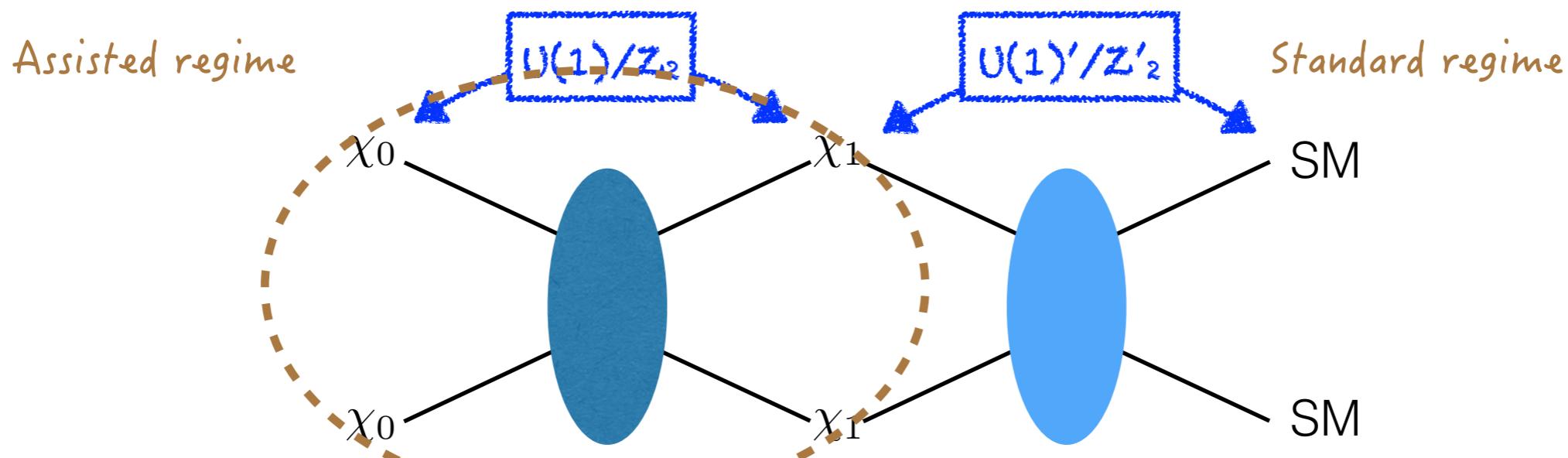
$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda_{\chi_1}(x)}{x} \left[Y_{\chi_1}^2 - (Y_{\chi_1}^{\text{eq}}(x))^2 \right] + \frac{\lambda_{\chi_0}(x)}{x} \left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\text{eq}}(x)}{Y_{\chi_1}^{\text{eq}}(x)} \right)^2 Y_{\chi_1}^2 \right],$$

with SM

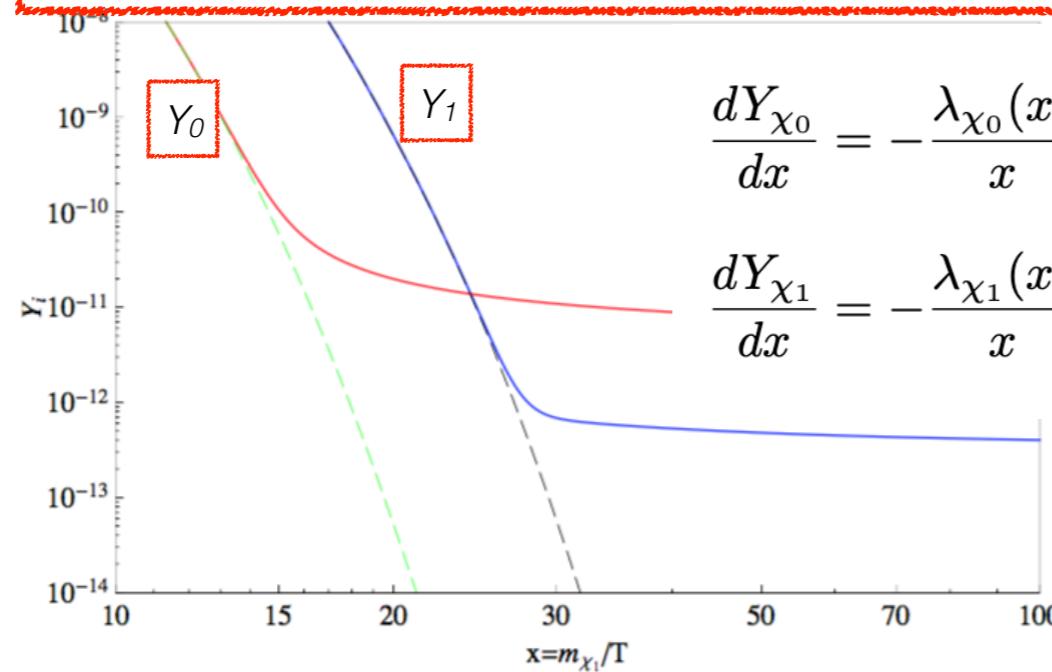
$$\lambda_{\chi_i} = s \langle \sigma_i v_{\text{rel}} \rangle / H$$

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with SM

with heavy DM χ_0

$$\lambda_{\chi_i} = s \langle \sigma_i v_{\text{rel}} \rangle / H$$

Structure of $\chi_1 \chi_1 \rightarrow \text{SM}$

After the heavy component χ_0 freezes-out

$$\frac{dY_{\chi_1}}{dx} \simeq -\frac{\lambda_{\chi_1}(x)}{x} \left[Y_{\chi_1}^2 - \underline{(Y_{\chi_1}^{\text{eq}}(x))^2} - Y_{\text{ast.}}^2(x) \right]$$



where $Y_{\text{ast.}}(x) = \sqrt{\frac{\langle \sigma_0 v_{\text{rel}} \rangle}{\langle \sigma_1 v_{\text{rel}} \rangle}} Y_{\chi_0}(x)$ $r_1 = \frac{\Omega_{\chi_1}}{\Omega_{\text{DM,tot}}}$

During the decoupling, assume χ_1 is in kinetic equilibrium with the SM

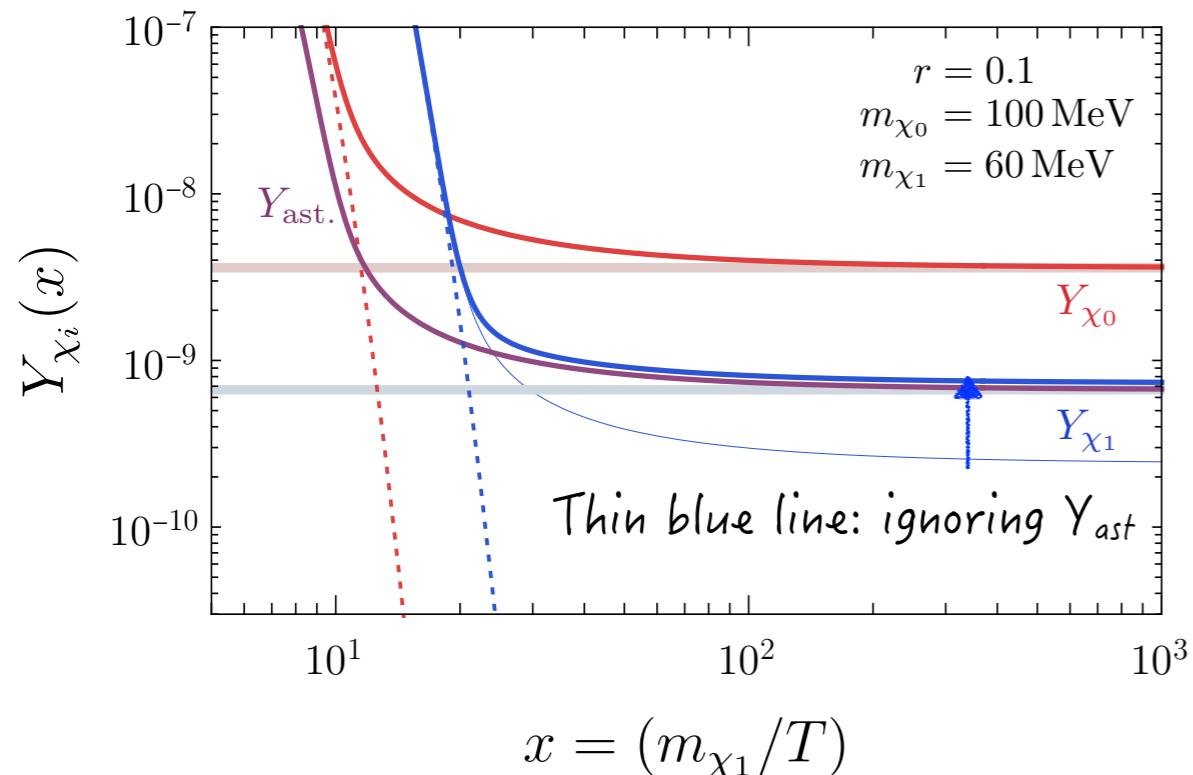
$$(\sigma_{\chi^0-\chi^1} < \sigma_{\chi^1-\text{SM}})$$

- If $Y_{\text{ast.}}$ is negligible, χ_1 freezes out at $T \sim m_1/20$ as usual. *Standard regime*
- If the fraction of χ_1 is very small, i.e., $r_1 \ll 1$, however, departure from thermal equilibrium is delayed and $Y_{\text{ast.}}$ is **non-negligible** compared to $Y_{\chi_1}^{\text{eq}}$

Assisted regime

Structure of $\chi_1\chi_1 \rightarrow \text{SM}$

When $\chi_1\chi_1 \rightarrow \text{SM}$ is dominated by s-wave



Assisted regime

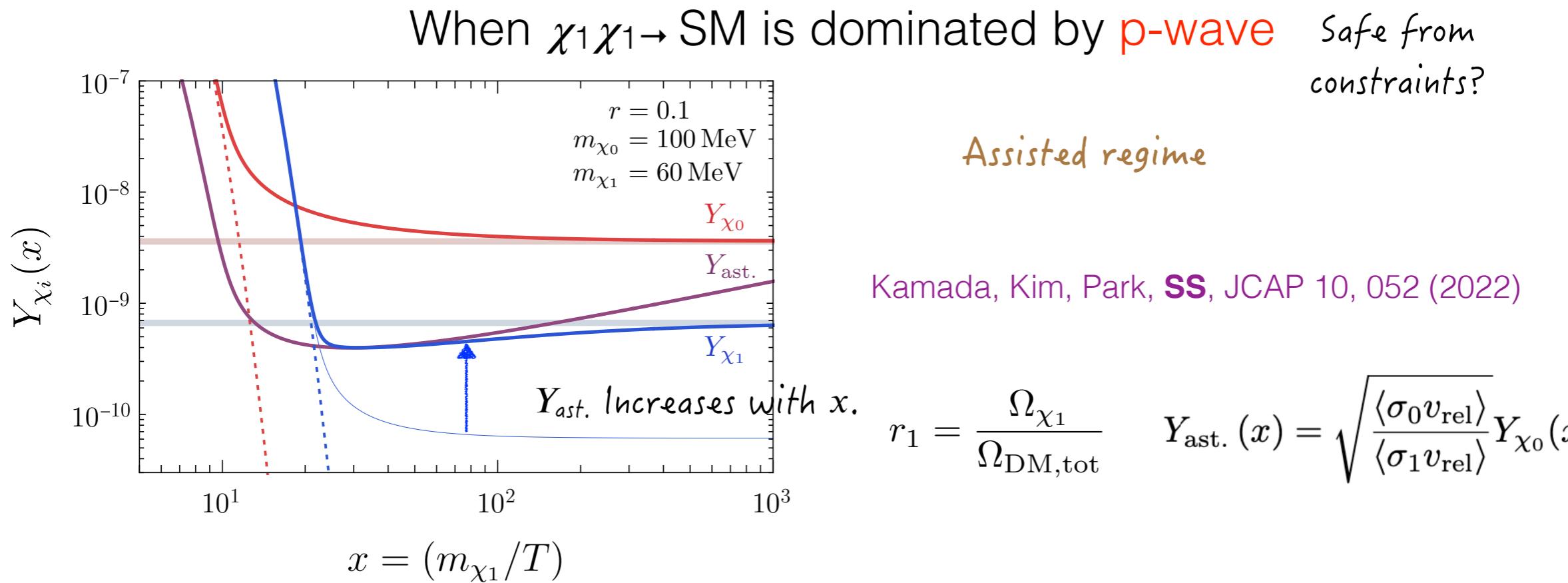
Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)

$$r_1 = \frac{\Omega_{\chi_1}}{\Omega_{\text{DM,tot}}} \quad Y_{\text{ast.}}(x) = \sqrt{\frac{\langle \sigma_0 v_{\text{rel}} \rangle}{\langle \sigma_1 v_{\text{rel}} \rangle}} Y_{\chi_0}(x)$$

- For $r_1 \ll 1$, Y_{χ_1} is lifted-up by $Y_{\text{ast.}}$ (follows it when $T \lesssim m_1/30$).
- The annihilation cross section $\chi_1\chi_1 \rightarrow \text{SM}$ is enhanced by $1/r_1^2$.

$$\langle \sigma_1 v_{\text{rel}} \rangle Y_{\chi_1}^2 \sim \langle \sigma_0 v_{\text{rel}} \rangle Y_{\chi_0}$$

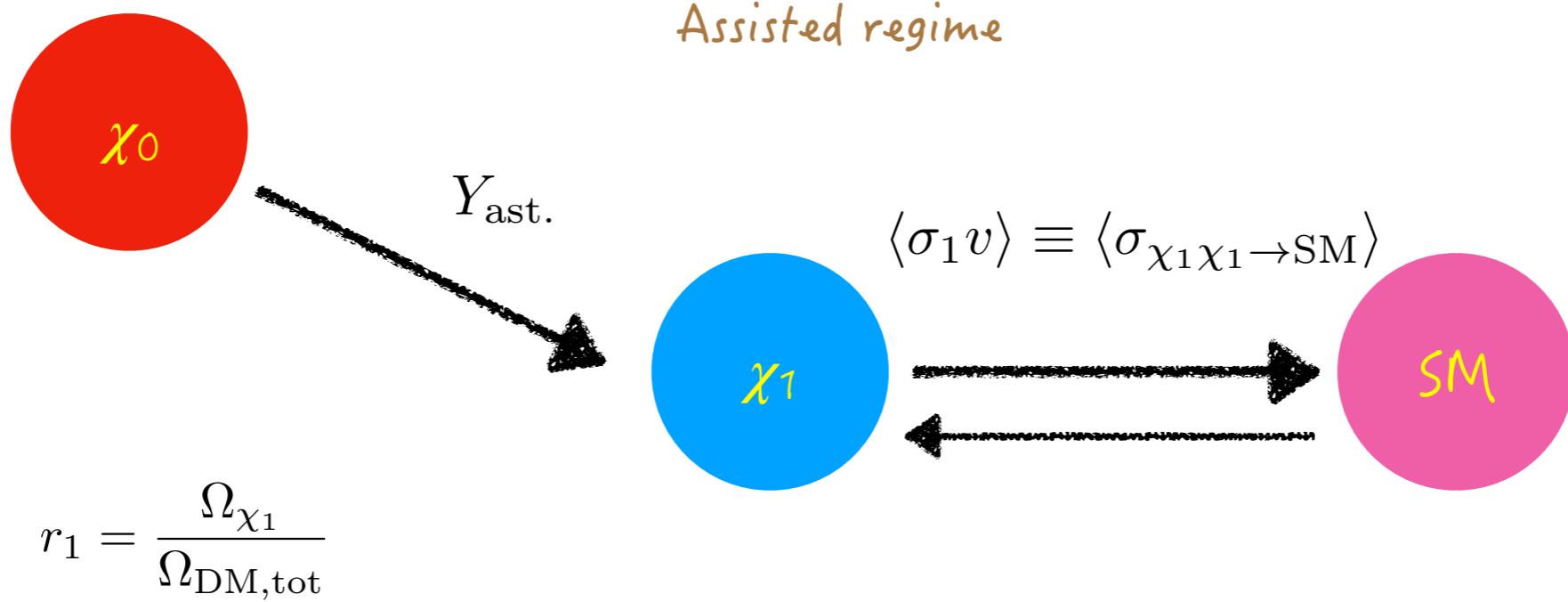
Structure of $\chi_1\chi_1 \rightarrow \text{SM}$



$$r_1 = \frac{\Omega_{\chi_1}}{\Omega_{\text{DM,tot}}} \quad Y_{\text{ast.}}(x) = \sqrt{\frac{\langle \sigma_0 v_{\text{rel}} \rangle}{\langle \sigma_1 v_{\text{rel}} \rangle}} Y_{\chi_0}(x)$$

- For $r_1 \ll 1$, Y_{χ_1} is lifted-up even more by $Y_{\text{ast.}}$ until $T \sim m_1/80$ (the contribution by p-wave $\chi_1\chi_1 \rightarrow \text{SM}$ gets relatively suppressed.)
- The annihilation cross section $\chi_1\chi_1 \rightarrow \text{SM}$ increases as $1/r_1^3$ so the process can be also sensitive to various observables.

Structure of $\chi_1\chi_1 \rightarrow \text{SM}$



- For a fixed $r_1 \ll 1$, $\chi_1\chi_1 \rightarrow \text{SM}$ should be even larger to deplete the contribution by the residual annihilation $\chi_0\chi_0 \rightarrow \chi_1\chi_1$ ($Y_{\text{ast.}}$).
 - We find $\langle\sigma_1 v\rangle \propto 1/r_1^2, 1/r_1^3$ for s-wave and p-wave, respectively.
- observables $\propto n_{\chi_1}^2 \langle\sigma_1 v\rangle \rightarrow$ No r_1 suppression!
(even enhanced)

Effects of χ_1 to various observables

Sub-component DM can be **not hidden** and $\chi_1\chi_1 \rightarrow \text{SM}$ affect

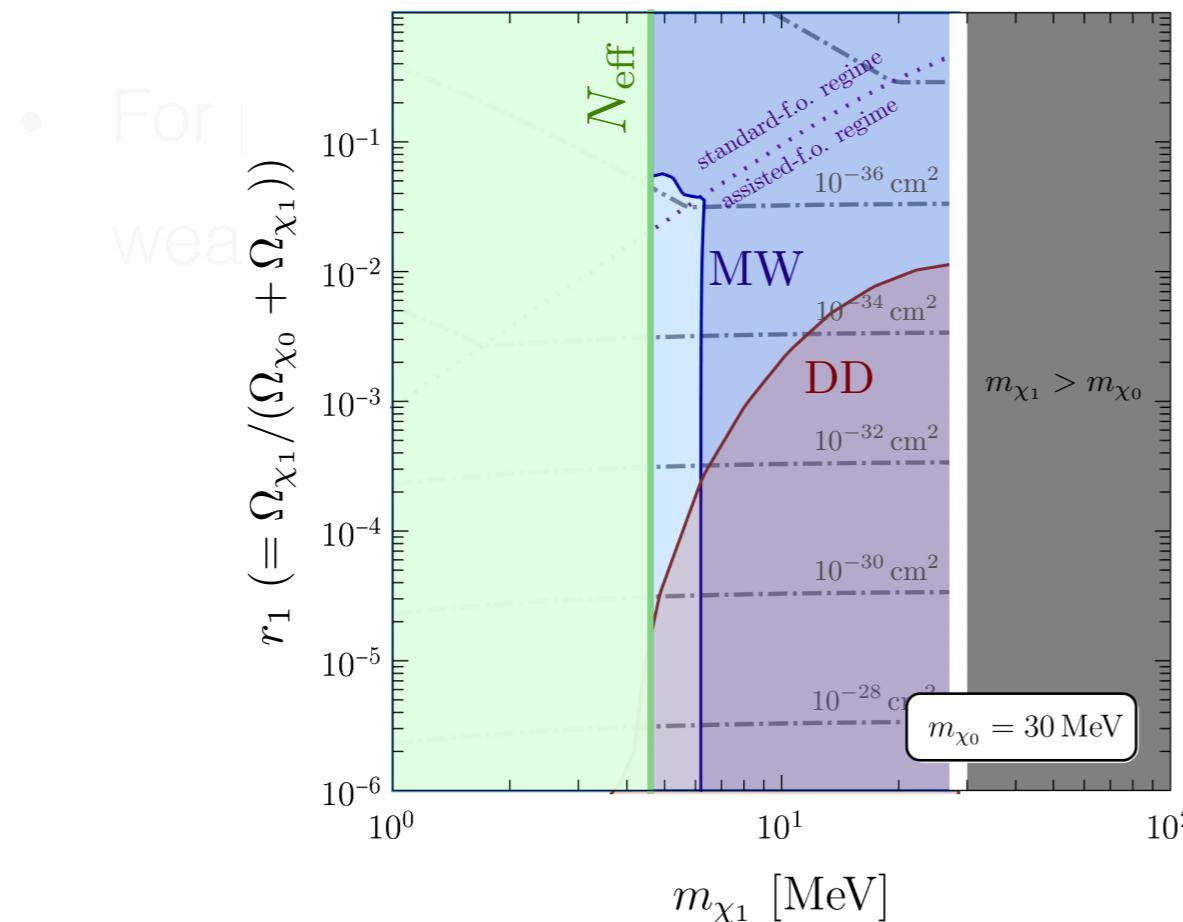
- Big Bang Nucleosynthesis: photo-dissociation of light elements
e.g., $e\gamma_b \rightarrow e'\gamma'$ changes the ratio of D, ${}^3\text{He}$, ${}^4\text{He}$, ..
- Cosmic microwave background: N_{eff} if χ_1 freeze-out at $T \lesssim T_{\nu,\text{dec}}$,
Energy injection by $\chi_1\chi_1 \rightarrow \text{SM}$ at the recombination epoch
- Diffuse X-rays and γ -rays in the Milky Way
- Direct detection if the crossing symmetry is effective.
(depending on the model)

Effects of χ_1 to various observables

Unprecedented role of a sub-dominant DM component

- For s-wave dominant $\chi_1\chi_1 \rightarrow \text{SM}$, the nominal constraints directly apply because $n_{\chi_1}^2 (\sigma_1 v_{\text{rel}})_s \sim r_1^2 \cdot \frac{1}{r_1^2} = \text{no } r_1$: **s-wave not preferred!**

(preconception: $n_{\chi_1}^2 \langle \sigma_1 v_{\text{rel}} \rangle_{\text{standard}} \sim r_1$ is not true!)



CMB bound (sky blue): disfavor the whole parameter space

Galactic diffuse X/γ -ray (deep blue)

N_{eff} (green): almost independent of r_1

Direct detection bound (brown): XENON10, 100, DarkSide-50

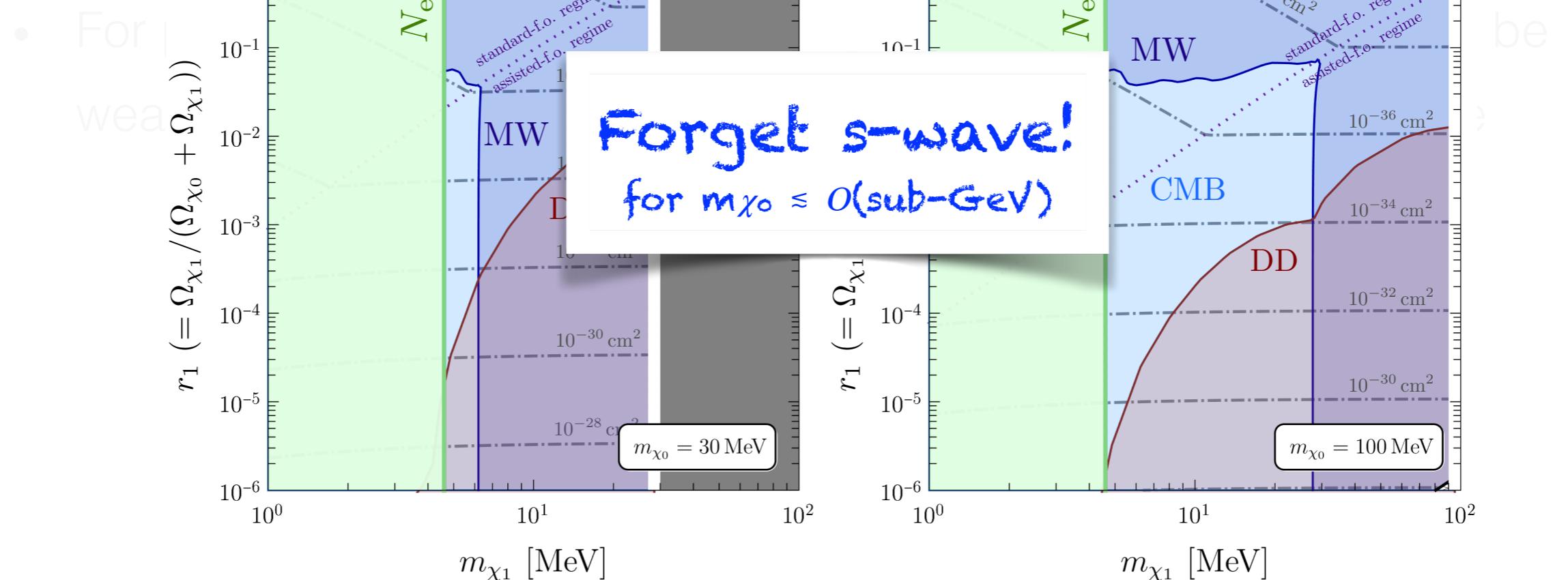
Effects of χ_1 to various observables

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$$n_{\chi_0} \downarrow \rightarrow Y_{\text{ast.}} \downarrow$$



Effects of χ_1 to various observables

Unprecedented role of a sub-dominant DM component

- For s-wave dominant $\chi_1\chi_1 \rightarrow \text{SM SM}$, the nominal constraints directly apply because $n_{\chi_1}^2 (\sigma_1 v_{\text{rel}})_s \sim r_1^2 \cdot \frac{1}{r_1^2} = \text{no } r_1$: **s-wave not preferred!**
(preconception: $n_{\chi_1}^2 \langle \sigma_1 v_{\text{rel}} \rangle_{\text{standard}} \sim r_1$ is not true!)
- For p-wave dominant $\chi_1\chi_1 \rightarrow \text{SM SM}$, the nominal constraints can be weaken by velocity suppression but its effect can be small since

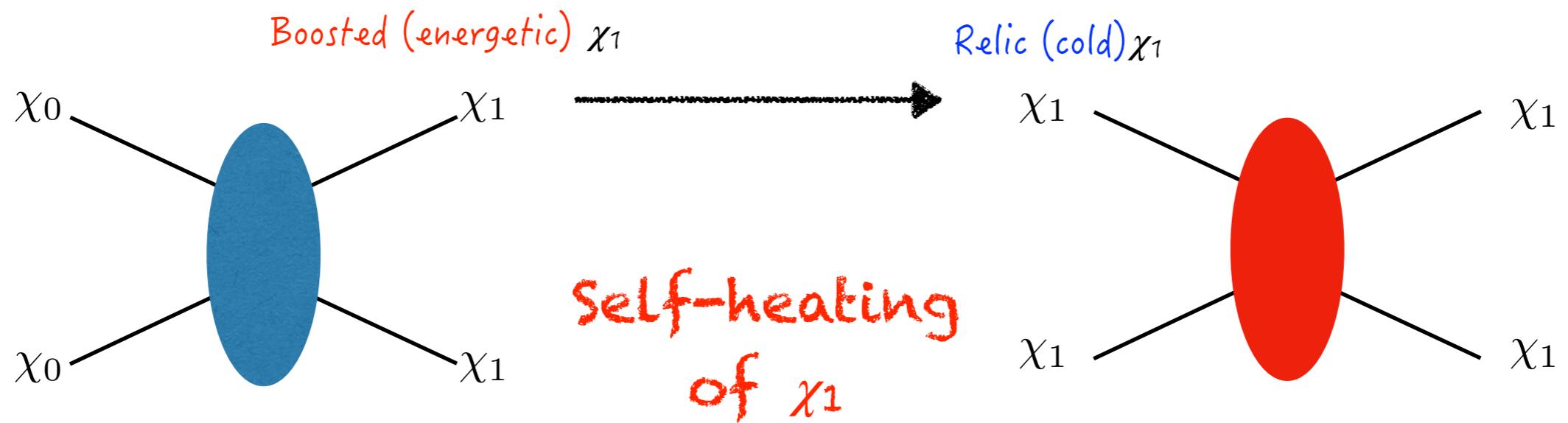
$$n_{\chi_1}^2 \langle \sigma_1 v_{\text{rel}} \rangle \sim r_1^2 \cdot \frac{1}{r_1^3} \cdot v^2 = \frac{v^2}{r_1}$$

$\chi_1 - \chi_1$
self-interaction

Sensitive to the evolution of the temperature of χ_1
in the early Universe

Self-heating of χ_1

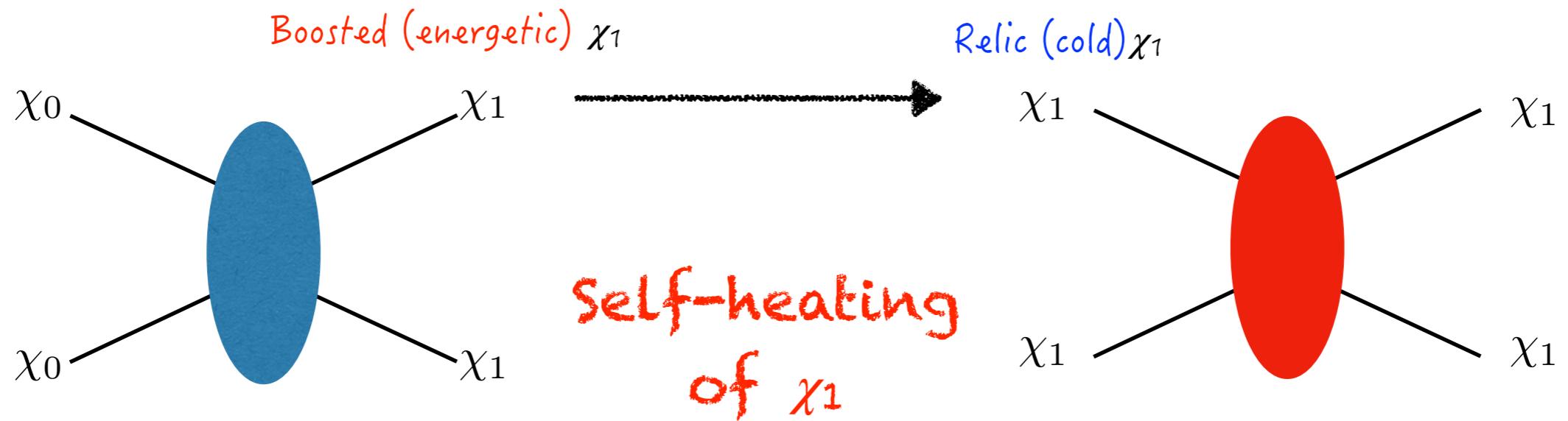
- Self-interacting DM models have been proposed actively recently.
- Self-interactions always exist. The question is how efficient they can transfer energy long after the freeze-out (not effective for WIMP).
- Self-interaction of a subdominant DM χ_1 can be large for the $O(1)$ dark sector coupling.



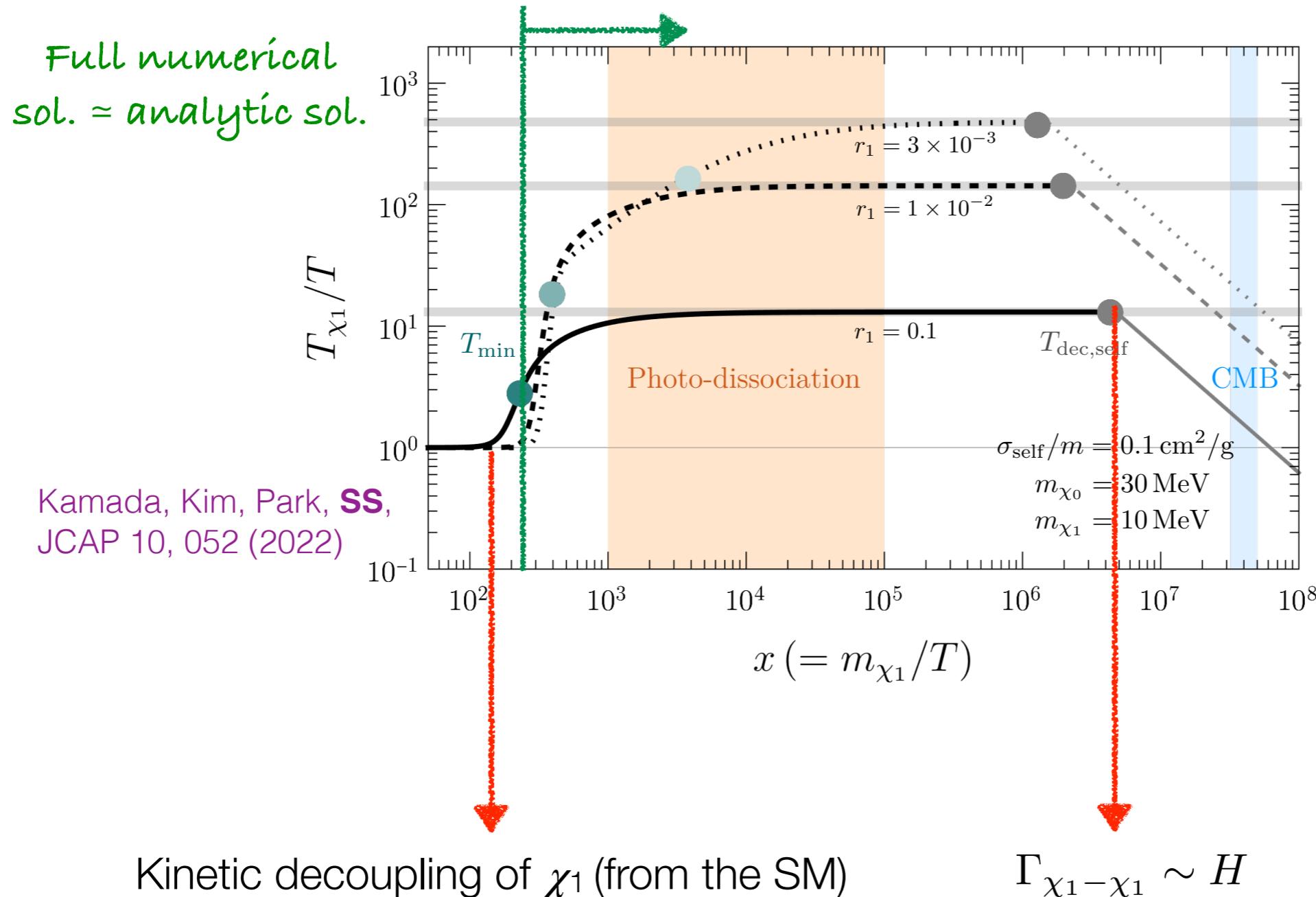
Self-heating of χ_1

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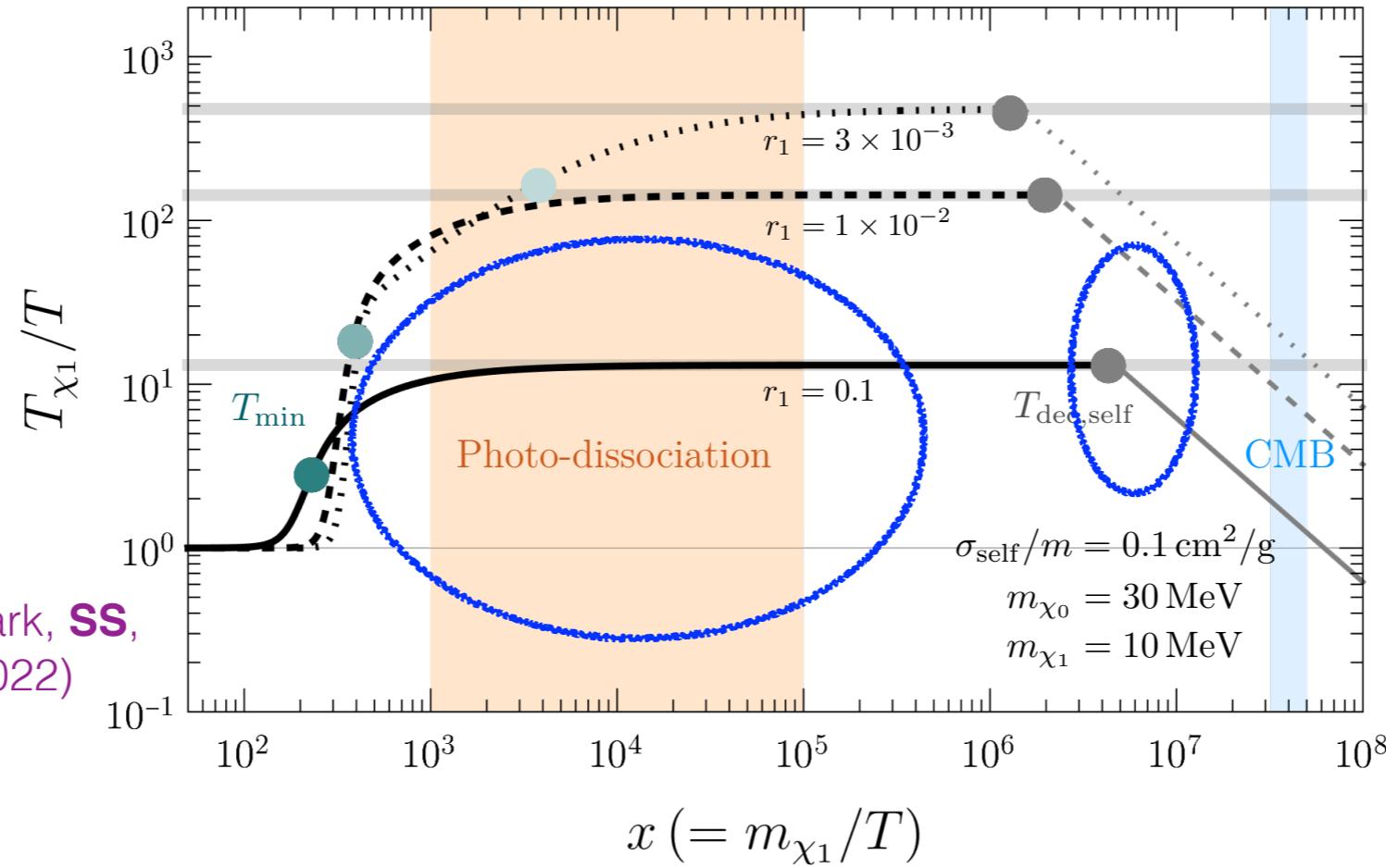
Temperature evolution of χ_1



- If self-heating is efficient even after the kinetic decoupling, the temperature evolution of χ_1 makes it behave like a radiation.

Temperature evolution of χ_1

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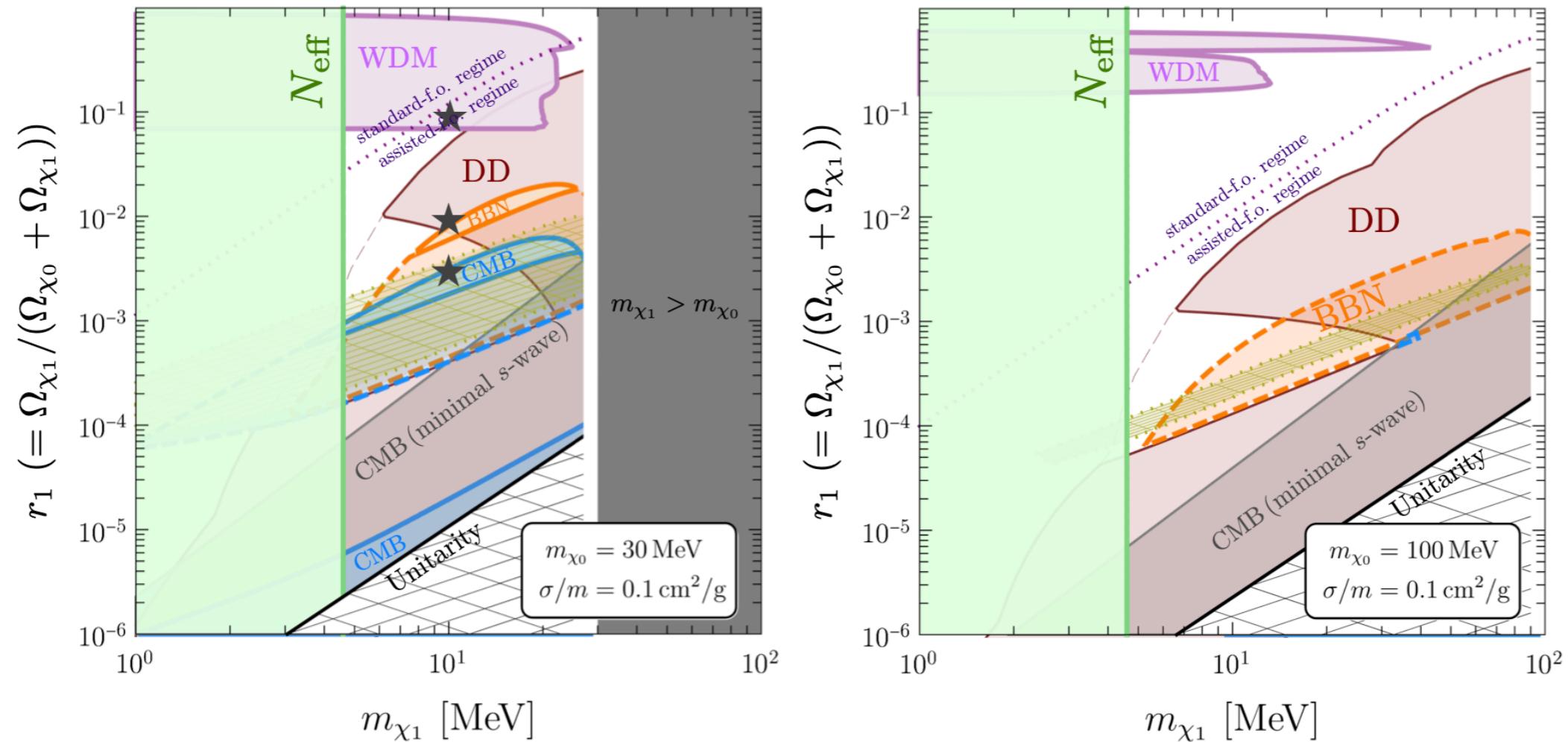
- Strong photo-dissociation bounds for $100 \text{ eV} \lesssim T \lesssim 10 \text{ keV}$ after BBN
- For $r_1 \gtrsim 0.07$, the self-heating epoch can persist even until the matter-radiation equality.

χ_1 can be **sub-GeV Warm Dark Matter!!**

Lyman- α
of satellites

New bounds due to self-heating

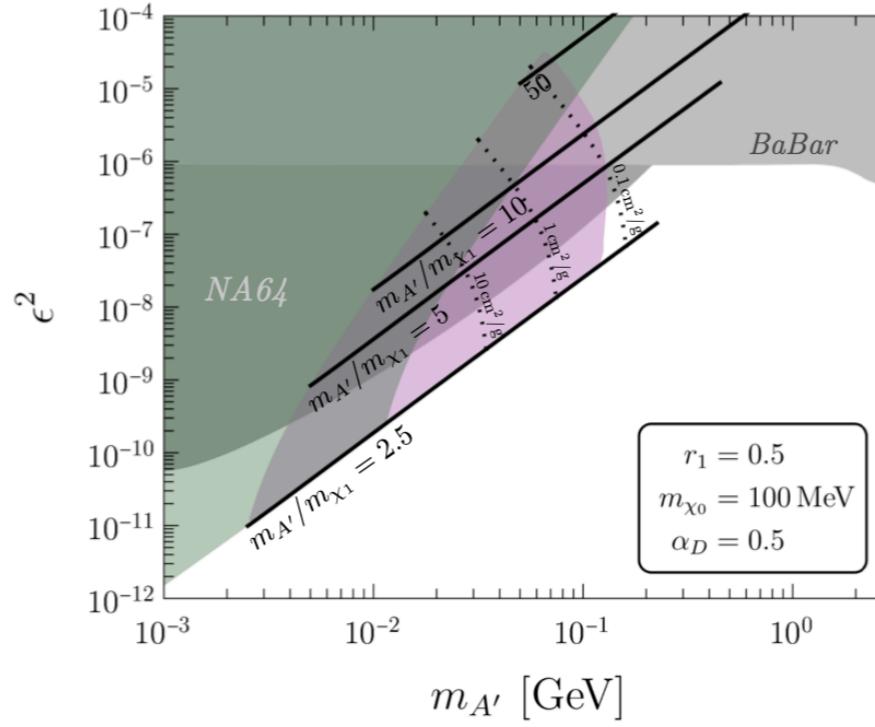
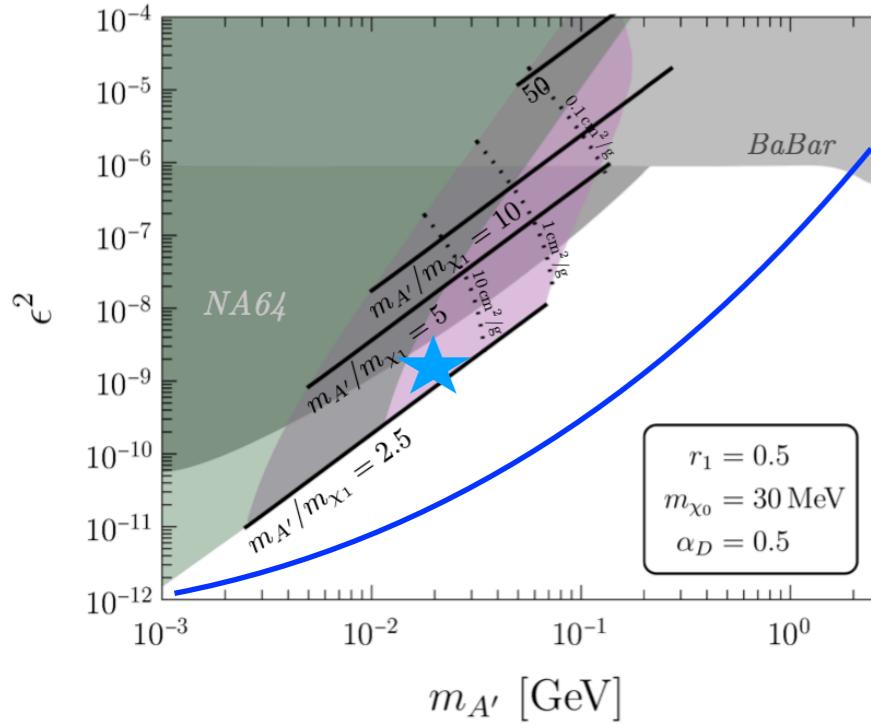
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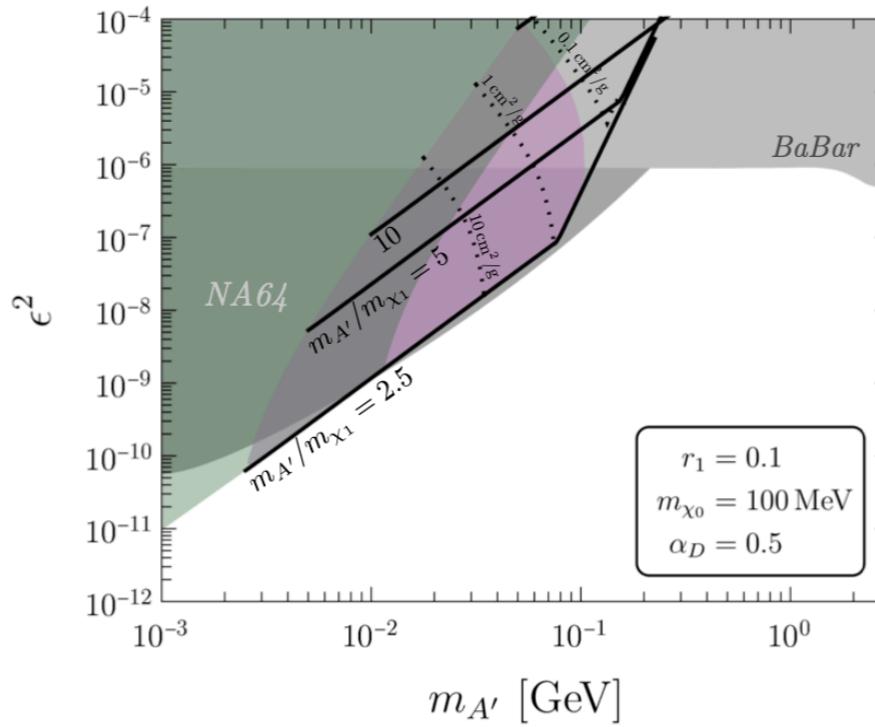
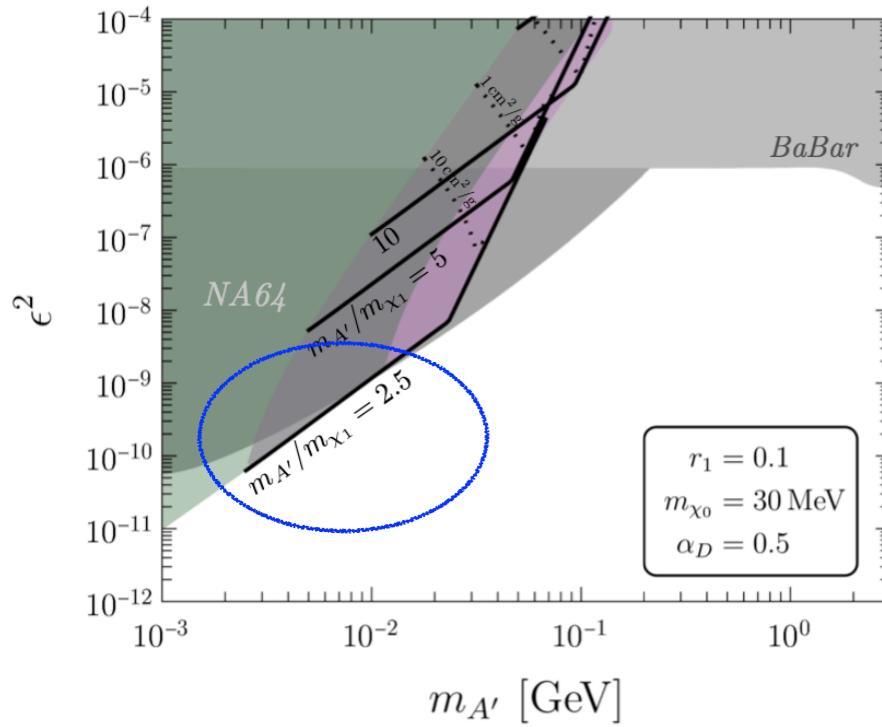
- WDM constraint enters when $r_1 \gtrsim 0.07$ even for $m_{\chi_1} \sim 40$ MeV.
- Direct detection bounds get weaken since n_{χ_1} inside our MW decreases due to the kinetic energy of χ_1
- ★: reference values of r_1 in the temperature evolution (previous slide)

Complementary searches

Light DM can be produced in accelerators with high intensities!



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- Reference model: **singlet scalar DM + dark photon (p-wave)**

- Green: N_{eff} ,
Pink: WDM
for $r_1 \gtrsim 0.07$.

- For $r_1 \lesssim 0.07$, not preferred by the accelerator results.

- Future discovery can tell the dark sector details.

Conclusions

- A **sub**-component DM (χ_1) can severely affect the cosmo/astro observables: p-wave χ_1 - SM is preferred but still constrained!.
(Multi-component p-wave scenarios are not always safe.)
- Self-heating naturally arises in a wide range of parameter space and changes the evolution of the temperature of χ_1 after the freeze-out.
- The temperature evolution affects the structure formation of χ_1 :
a **sub-GeV mass Warm Dark Matter** (heavy WDM) for $r_1 \gtrsim 0.07$!
→ This is true even when χ_1 is a dominant component DM.
- Complementary searches in accelerators can give hints on the dark sector details (disfavor $r_1 \lesssim 0.07$ for a reference model).



Public

Asia/Seoul

S. Shin

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12–16 Jun 2023

IBS

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The 16th International Conference on Interconnections between Particle Physics and Cosmology (PPC 2023), hosted by the Institute for Basic Science (IBS) will take place in Daejeon, Korea, June 12–16.

PPC aims to bring together the world-class experts in particle physics, cosmology, and astrophysics for active discussions and interdisciplinary collaborations among different fields. We hope to provide exciting opportunities to develop new directions and/or breakthroughs in understanding the principles of our universe.

PPC 2023 will be followed by a satellite workshop on Boosted Dark Matter (BDM) which will be announced soon.

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- Cosmology
- Dark Matter Physics
- Flavor Physics
- Gravitational Waves
- Neutrino Physics

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